

MEASUREMENTS OF CHARMED MESON LIFETIMES AND SEARCH FOR D^0 - \bar{D}^0 MIXING WITH THE BELLE EXPERIMENT

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The lifetimes of charmed mesons have been measured using 11.1 fb^{-1} of data collected with the Belle detector at KEKB. Each candidate is fully reconstructed to identify the flavor of the charmed meson. The lifetimes are measured to be $\tau(D^0) = (414.5 \pm 1.7(\text{stat.})) \text{ fs}$, $\tau(D^+) = (1029 \pm 12(\text{stat.})) \text{ fs}$ and $\tau(D_s^+) = (488.4^{+7.8}_{-7.7}(\text{stat.})) \text{ fs}$, where the error is statistical only. The ratios of the lifetimes of D^+ and D_s^+ with respect to D^0 are measured to be $\tau(D^+)/\tau(D^0) = 2.48 \pm 0.03(\text{stat.})$ and $\tau(D_s^+)/\tau(D^0) = 1.18 \pm 0.02(\text{stat.})$. The mixing parameter y_{CP} is also measured to be $y_{CP} = (1.16^{+1.67}_{-1.65}(\text{stat.})) \%$ through the lifetime difference of D^0 mesons decaying into CP-mixed states and CP eigenstates. All results are preliminary.

1 Introduction

Measurements of individual charmed meson lifetimes provide useful information for the theoretical understanding of the heavy flavor decay mechanisms^{1,2}. Moreover, the D^0 - \bar{D}^0 mixing parameters, $y \equiv (\Gamma_H - \Gamma_L)/(\Gamma_H + \Gamma_L)$ and $x \equiv 2(M_H - M_L)/(\Gamma_H + \Gamma_L)$, can be explored by measuring the lifetime difference of the D^0 meson decaying into a CP-mixed state $D^0 \rightarrow K^-\pi^+$ and a CP-eigenstate $D^0 \rightarrow K^-K^+$. The parameter y_{CP} , defined by $y_{CP} \equiv \frac{\Gamma(\text{CP even}) - \Gamma(\text{CP odd})}{\Gamma(\text{CP even}) + \Gamma(\text{CP odd})} = \frac{\tau(D^0 \rightarrow K^-\pi^+)}{\tau(D^0 \rightarrow K^-K^+)} - 1$, is related to y and x by the expression $y_{CP} = y \cos \phi - \frac{A_{mix}}{2} x \sin \phi$, where ϕ is a CP violating weak phase due to the interference of decays with and without mixing, and A_{mix} is related to CP violation in mixing. E791^{3,4}, FOCUS⁵ and CLEO⁷ have measured $y_{CP} = (0.8 \pm 2.9 \pm 1.0)\%$, $y_{CP} = (3.42 \pm 1.39 \pm 0.74)\%$ and $y_{CP} = (-1.1 \pm 2.5 \pm 1.4)\%$ respectively. It is interesting that the FOCUS result is non-zero by more than two standard deviations. On the other hand, CLEO⁶ gives results for D^0 - \bar{D}^0 mixing through $D^0 \rightarrow K^+\pi^-$, $y' \cos \phi = (-2.5^{+1.4}_{-1.6})\%$, $x' = (0.0 \pm 1.5 \pm 0.2)\%$ and $A_{mix} = 0.23^{+0.63}_{-0.80}$, where $y' = y \cos \delta - x \sin \delta$ and $x' = x \cos \delta + y \sin \delta$; the parameter δ is the strong phase between the doubly Cabibbo suppressed decay $D^0 \rightarrow K^+\pi^-$ and the Cabibbo allowed decay $\bar{D}^0 \rightarrow K^+\pi^-$ ($\delta = 0$ in the $SU(3)$ limit). The FOCUS and CLEO results could be consistent if there is a large $SU(3)$ breaking effect in $D^0 \rightarrow K^\pm\pi^\mp$ decays⁸.

2 B-Factory

2.1 Accelerator: KEKB

The KEKB¹⁰ is an asymmetric energy electron-positron collider designed to boost B mesons. The electron and positron beam energies are 8 GeV and 3.5 GeV respec-

tively: the resulting CMS energy, 10.58 GeV, corresponds to the the mass of the $\Upsilon(4S)$ resonance. At the design luminosity, $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, about 10^8 $\Upsilon(4S)$ are produced per year. So-called continuum events ($e^+e^- \rightarrow u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$) are also produced, in the ratio $q\bar{q}:\Upsilon(4S) \simeq 3.5:1$.

2.2 Detector: Belle

The Belle detector¹¹ consists of a three-layer silicon vertex detector(SVD), a 50-layer central drift chamber(CDC), an array of 1188 aerogel Čerenkov counters(ACC), 128 time-of-flight(TOF) scintillation counters, an electromagnetic calorimeter containing 8736 CsI(Tl) crystals(ECL) and 14 layers of 4.7-cm-thick iron plates interleaved with a system of resistive plate counters(KLM). All subdetectors, apart from the KLM, are located inside a 3.4-m-diameter superconducting solenoid that provides a 1.5 Tesla magnetic field. The transverse momentum resolution for charged tracks is $(\sigma_{p_T}/p_T)^2 = (0.00019 p_T)^2 + (0.0034)^2$, where p_T is in GeV/c and the impact parameter resolution for $p=1 \text{ GeV}/c$ tracks at normal incidence is $\sigma_{r\phi} \simeq \sigma_z = 55 \mu\text{m}$. dE/dz measurements in the CDC ($\sigma_{dE/dz}=6.9\%$), TOF flight-time measurements ($\sigma_{TOF}=95 \text{ ps}$) and the response of the ACC provide K^\pm identification with an efficiency of about 85% and a charged pion fake rate of about 10% for all momenta up to 3.5 GeV/c. Photons are identified as ECL showers that have a minimum energy of 20 MeV and are not matched to a charged track. The photon energy resolution is $(\sigma_E/E)^2 = (0.013)^2 + (0.0007/E)^2 + (0.008/E^{1/4})^2$, where E is in GeV.

3 Reconstruction

D^0 , D^+ and D_s^+ mesons are fully reconstructed via the decay chains^a $D^0 \rightarrow K^-\pi^+$, $D^0 \rightarrow K^-K^+$, $D^+ \rightarrow$

^aCharge-conjugate modes are implied throughout this paper.

$K^-\pi^+\pi^+$ (with $D^{*+} \rightarrow D^+\pi^0$ requirement), $D^+ \rightarrow \phi\pi^+$, $\phi \rightarrow K^+K^-$, $D_s^+ \rightarrow \phi\pi^+$, and $D_s^+ \rightarrow \bar{K}^{*0}K^+$, $\bar{K}^{*0} \rightarrow K^-\pi^+$.

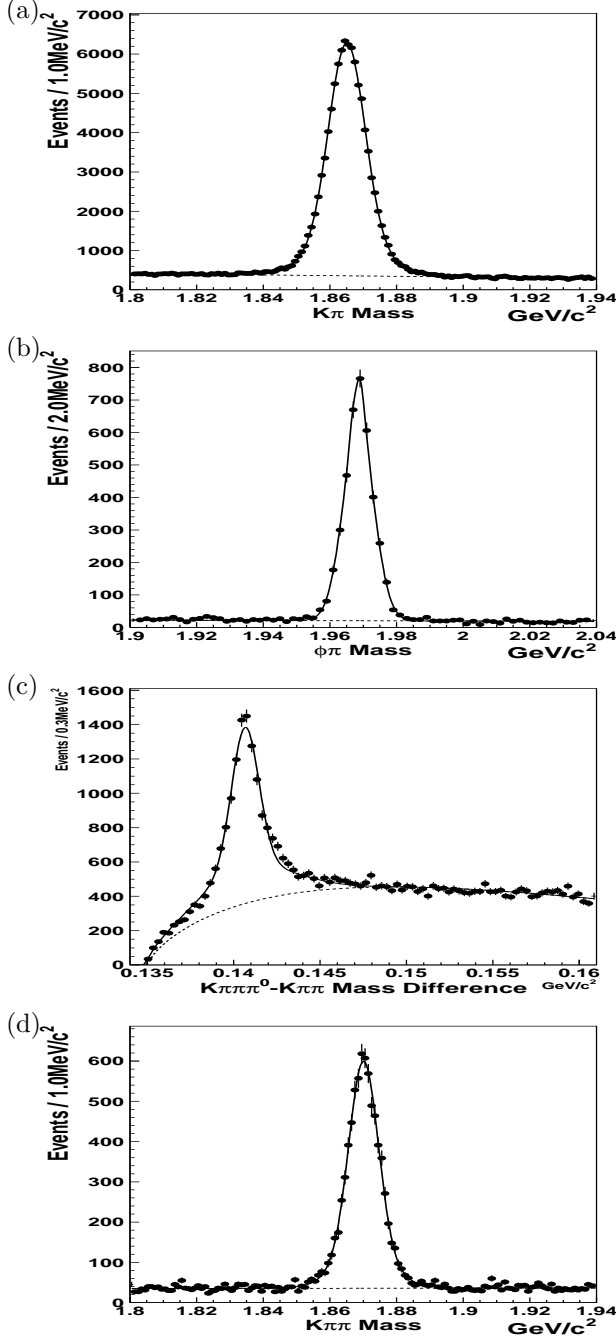


Figure 1: Mass and mass difference distributions: (a) $D^0(K^-\pi^+)$, (b) $D_s^+(\phi\pi^+)$, (c) $D^{*+} - D^+$ and (d) $D^+(K^-\pi^+\pi^+)$.

The charmed meson momentum in the $\Upsilon(4S)$ rest frame is required to be greater than 2.5 GeV/c to eliminate $B\bar{B}$ events which do not come from the interaction region. The other selection criteria, *e.g.* cuts on

the decay angle, the helicity angle and $\chi^2/\text{N.D.F}$ of the track fit, are described in detail in the conference paper⁹ of ICHEP2000. Figures 1 show mass and mass difference ($m_{D^{*+}} - m_{D^+}$) distributions for some decay chains of the D^0 , D^+ and D_s^+ . We find 90601 ± 387 $D^0 \rightarrow K^-\pi^+$, 7451 ± 118 $D^0 \rightarrow K^-K^+$, 6953 ± 99 $D^+ \rightarrow K^-\pi^+\pi^+$ signals with $D^{*+} \rightarrow D^+\pi^0$ requirement, 1137 ± 35 $D^+ \rightarrow \phi\pi^+$, 3757 ± 54 $D_s^+ \rightarrow \phi\pi^+$ and 2207 ± 68 $D_s^+ \rightarrow \bar{K}^{*0}K^+$ signals within 3σ of the measured mean value.

The decay vertex (\mathbf{x}_{dec}) of the charmed meson is determined and then the production vertex (\mathbf{x}_{pro}) is obtained by extrapolating the D flight path to the interaction region of e^+e^- . The projected decay length (L) and the proper-time (t) are obtained from $L = (\mathbf{x}_{pro} - \mathbf{x}_{dec}) \cdot \mathbf{p}_D / |\mathbf{p}_D|$ and $t = Lm_D / c|\mathbf{p}_D|$ respectively, where \mathbf{p}_D and m_D are the momentum and mass of the charmed meson.

4 Lifetime Fit

An unbinned maximum likelihood fit is performed to extract the lifetimes. The probability density function (P) for each event consists of a signal term and two background terms, representing components of the background with non-zero lifetime and zero lifetime respectively. The likelihood function (L) is then given by

$$\begin{aligned}
 L &= \prod_i P(t^i, \sigma_t^i, f_{SIG}^i) \\
 &= \prod_i [f_{SIG}^i \int_0^\infty dt' \frac{1}{\tau_{SIG}} e^{-\frac{t'}{\tau_{SIG}}} R_{SIG}(t^i - t', \sigma_t^i) \\
 &\quad + (1 - f_{SIG}^i) \int_0^\infty dt' \{f_{\tau_{BG}} \frac{1}{\tau_{BG}} e^{-\frac{t'}{\tau_{BG}}} \\
 &\quad + (1 - f_{\tau_{BG}}) \delta(t')\} R_{BG}(t^i - t', \sigma_t^i)],
 \end{aligned}$$

where f_{SIG}^i and $f_{\tau_{BG}}$ are fractions for the signal and the background with lifetime, τ_{SIG} and τ_{BG} are the signal and background lifetimes, R_{SIG} and R_{BG} are the resolution functions for the signal and the background, and t^i , σ_t^i are the measured proper-time, and its error, for each event. The fraction f_{SIG}^i is obtained based on the charmed meson mass for each event. Since f_{SIG}^i distributes an event to signal and background contributions properly, we fit lifetimes in a wide range ($\pm 40 \text{ MeV}/c^2$) of the D mass, that is, in signal and sideband regions simultaneously. The resolution functions R_{SIG} and R_{BG} are represented using

$$\begin{aligned}
 R(t, \sigma_t) &= (1 - f_{tail}) \frac{1}{\sqrt{2\pi} S \sigma_t} e^{-\frac{t^2}{2S^2 \sigma_t^2}} \\
 &\quad + f_{tail} \frac{1}{\sqrt{2\pi} S_{tail} \sigma_t} e^{-\frac{t^2}{2S_{tail}^2 \sigma_t^2}},
 \end{aligned}$$

where S and S_{tail} are global scaling factors for the estimated error σ_t for the main and tail Gaussian distributions and f_{tail} is the fraction of the tail part.

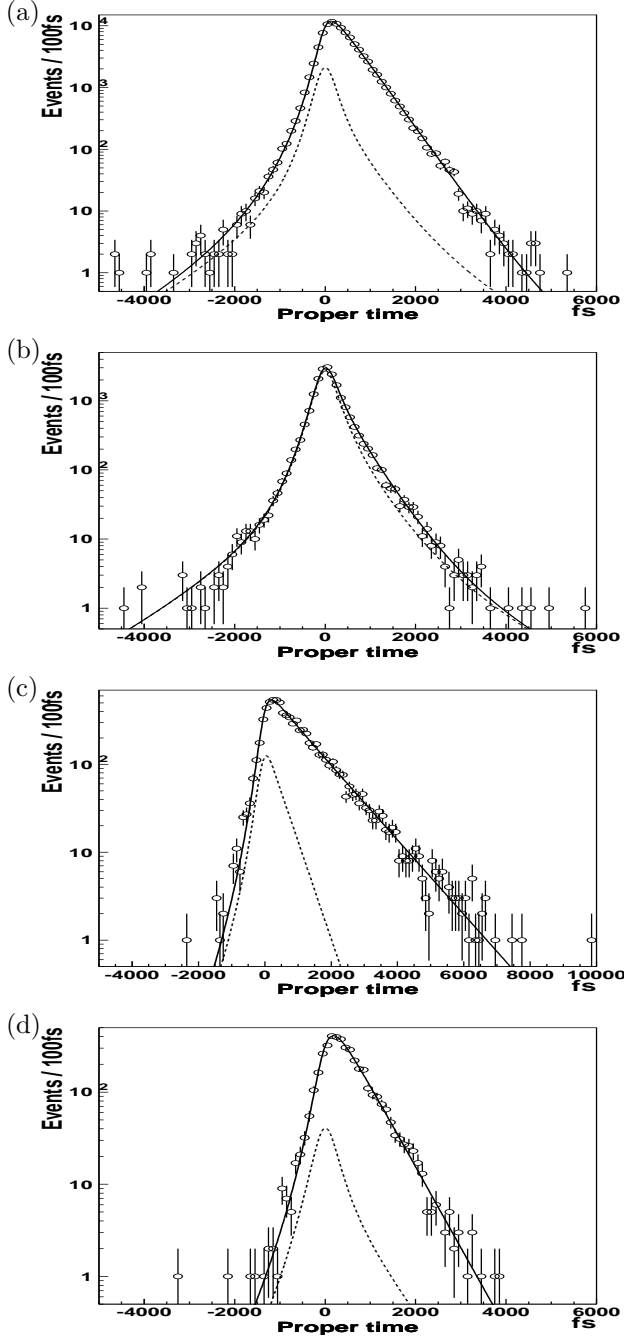


Figure 2: Proper-time distributions: signal regions of $D^0 \rightarrow K^-\pi^+$ (a), $D^+ \rightarrow K^-\pi^+\pi^+$ (c), $D_s^+ \rightarrow \phi\pi^+$ (d), and a background region of $D^0 \rightarrow K^-\pi^+$ (b), where a circle is data, a solid curve is signal and background and a dotted curve is background estimated from the fit result.

Figures 2 show the proper-time distributions and fit results for $D^0 \rightarrow K^-\pi^+$, $D^+ \rightarrow K^-\pi^+\pi^+$ and

$D_s^+ \rightarrow \phi\pi^+$. We plot them in signal ($< \pm 3\sigma$) and sideband ($> \pm 3\sigma$) regions in order to check whether our fits are good. From the sideband region plot we can see that our background estimation is good.

We use a combined likelihood to obtain y_{CP} and the D^+ and D_s^+ lifetimes, since two final states are analyzed in each case. This method makes it easier to estimate correlated systematic errors, *e.g.* interaction point uncertainties. The combined likelihoods are defined as

$$\begin{aligned} L_{y_{CP}} &= L_{D^0 \rightarrow K^-\pi^+} \cdot L_{D^0 \rightarrow K^-K^+}, \\ L_{D^+} &= L_{D^+ \rightarrow K^-\pi^+\pi^+} \cdot L_{D^+ \rightarrow \phi\pi^+}, \\ L_{D_s^+} &= L_{D_s^+ \rightarrow \phi\pi^+} \cdot L_{D_s^+ \rightarrow \bar{K}^{*0}K^+}. \end{aligned}$$

In L_{D^+} and $L_{D_s^+}$ a common τ_{SIG} is used, *i.e.*,

$$\begin{aligned} \tau_{SIG D^+} &= \tau_{SIG D^+ \rightarrow K^-\pi^+\pi^+} = \tau_{SIG D^+ \rightarrow \phi\pi^+} \\ \tau_{SIG D_s^+} &= \tau_{SIG D_s^+ \rightarrow \phi\pi^+} = \tau_{SIG D_s^+ \rightarrow \bar{K}^{*0}K^+}. \end{aligned}$$

In $L_{y_{CP}}$ the lifetime parameter of $D^0 \rightarrow K^-K^+$, $\tau_{SIG D^0 \rightarrow K^-K^+}$, is calculated from

$$\tau_{SIG D^0 \rightarrow K^-K^+} = \tau_{SIG D^0 \rightarrow K^-\pi^+} / (1 + y_{CP}).$$

Figure 3 shows the log-likelihood, as a function of y_{CP} , which is obtained from the combined fit method.

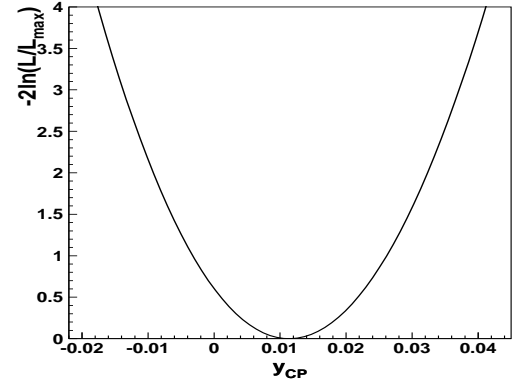


Figure 3: Log-likelihood as a function of y_{CP} .

5 Systematic Uncertainties

We consider systematic uncertainties from the reconstruction of the D decay length and from the fit function. We take into account decay vertex uncertainties, vertexing cut dependence, uncertainties of the Monte Carlo correction, the size and position uncertainties of the interaction point, mass dependence of the proper-time, D -mass sideband region dependence and so on. The first, second and third items are the major sources of systematic error. Since we are still studying these systematic uncertainties, we do not quote them here.

Table 1: Comparison of our results with PDG world averages and recent measurements.

Experiment	$\tau(D^0)$ fs	$\tau(D^+)$ fs	$\tau(D_s^+)$ fs	y_{CP} %
PDG ¹²	412.6 ± 2.8	1051 ± 13	496^{+10}_{-9}	—
E791	$(413 \pm 3 \pm 4)^\dagger$	—	$(518 \pm 14 \pm 7)^\dagger$	$0.8 \pm 2.9 \pm 1.0$
CLEO	$(408.5 \pm 4.1^{+3.5}_{-3.4})^\dagger$	$(1034 \pm 22^{+10}_{-13})^\dagger$	$(486 \pm 15 \pm 5)^\dagger$	$-1.1 \pm 2.5 \pm 1.4$
FOCUS	$409.2 \pm 1.3^\ddagger$	—	$506 \pm 8^\ddagger$	$3.42 \pm 1.39 \pm 0.74$
Belle	$414.5 \pm 1.7(stat.)$	$1029 \pm 12(stat.)$	$488.4^{+7.8}_{-7.7}(stat.)$	$1.16^{+1.67}_{-1.65}(stat.)$

[†]This result is included in the PDG2000 world average.

[‡]No systematic error is given.

6 Doubly Cabibbo-Suppressed Decay

We are also studying wrong-sign decays $D^0 \rightarrow K^+\pi^-$ to measure x' and y' from the proper-time distribution of wrong-sign decays. We can see a clear peak in the $Q(=m_{D^*} - m_{D^0} - m_\pi)$ distribution for wrong-sign decays, as shown in Figure 4 and are still studying the various background components, and their distributions in (Q, m_{D^0}) .

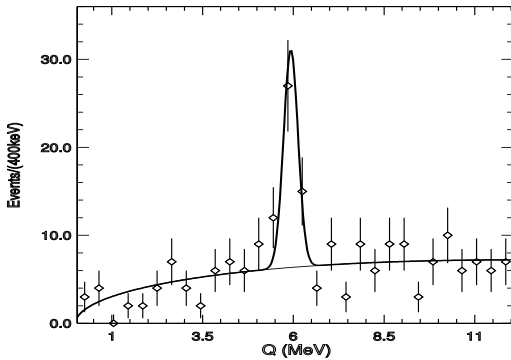


Figure 4: Q distribution of wrong-sign decay $D^0 \rightarrow K^+\pi^-$.

7 Conclusions

We have presented new measurements of charmed meson lifetimes using 11.1 fb^{-1} of data sample collected with the Belle detector near the $\Upsilon(4S)$ energy. Unbinned maximum likelihood fits to proper-time distributions of fully reconstructed charmed meson candidates yield results for the lifetime and the mixing parameter y_{CP} as shown in Table 1. The measured value of y_{CP} is consistent with zero. We need more data to measure it more precisely and test the FOCUS result. The statistical uncertainties on the lifetimes are better than those of the best published measurements. All results are preliminary.

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